

# Quantification of Plume Opacity by Digital Photography

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The United States Environmental Protection Agency (USEPA) developed Method 9 to describe how plume opacity can be quantified by humans. However, use of observations by humans introduces subjectivity, and is expensive due to semiannual certification requirements of the observers. The Digital Opacity Method (DOM) was developed to quantify plume opacity at lower cost, with improved objectivity, and to provide a digital record. Photographs of plumes were taken with a calibrated digital camera under specified conditions. Pixel values from those photographs were then interpreted to quantify the plume's opacity using a contrast model and a transmission model. The contrast model determines plume opacity based on pixel values that are related to the change in contrast between two backgrounds that are located behind and next to the plume. The transmission model determines the plume's opacity based on pixel values that are related to radiances from the plume and its background. DOM was field tested with a smoke generator. The individual and average opacity errors of DOM were within the USEPA Method 9 acceptable error limits for both field campaigns. Such results are encouraging and support the use of DOM as an alternative to Method 9.

## Introduction

Emissions of particulate matter from anthropogenic sources draw public attention because of their adverse impact on human health and the aesthetics of our environment. For example, the Regional Haze Rule was adopted during 1999 to protect visual air quality by reducing anthropogenic emissions to the extent that visibility is not noticeably degraded more than it would be under natural conditions (1). The United States Environmental Protection Agency (USEPA) and state authorities enforce both mass emission and opacity standards for stationary sources of particulate matter. Opacity standards are reportedly more lenient than the corresponding mass emission standards, so a violation of an opacity standard is an indication of a violation of the mass emission standard (2).

Method 9, as developed by USEPA, quantifies the opacity of plumes that are emitted from stationary sources. Method 9 requires a certified observer to visually determine the plume's opacity once every 15 s for 6 min. However, Method

9 does not provide an archival graphical record of the plume and there are concerns about the method's subjectivity (3). The visual appearance of a plume can be affected by many factors, such as the angle of the sun, the time of day, and the geographic location of the source (4). To be certified, the observer needs to be trained during "smoke school" and pass an opacity measurement field test on a semiannual basis. Such requirements make Method 9 labor-intensive and expensive. The accuracy of a smoke reader to quantify plume opacity using Method 9 depends on the plume's background and environmental conditions, which may impose limitations on the visual evaluation of the plumes by humans (5).

Controllable factors that determine plume opacity in the atmosphere include the orientation of the observer, plume, and sun, time of the day when the observation is made, distance between the plume and observer, and availability of backgrounds for the plume. Uncontrollable factors include change in naturally existing backgrounds (e.g., clear vs cloudy sky), height of the stack, and meteorology. These factors demonstrate the difficulties experienced when measuring plume opacities in the ambient environment. For example, a plume is most visible and presents the greatest apparent opacity when viewed against a contrasting background, and its opacity can be estimated with the greatest degree of accuracy. However, if the contrast between the plume and its background decreases toward zero, the apparent opacity also approaches zero. As a result, a negative bias will be made during low contrasting conditions between the plume and its background.

Quantification of ambient visual range and plume opacity with photography can lower costs, improve accuracy and precision, reduce subjectivity, and provide a photograph as an archival record. The fundamental relationship between visual range, contrast, and the scattering coefficient was initially derived more than 80 years ago (6). Visual range of an ambient environment's vista was initially quantified using a film camera and a digitizer (7). These photographs were then used to calculate visual range for clear-sky conditions. First principles needed to simulate the effect of uniform haze photographically were described and verified experimentally during the 1980s (8, 9). Also, equations were developed to describe atmospheric transmittance and path radiance when using two cameras that took pictures of the same scene at different distances (10). Optical measurements of transmission and scattered radiances for a ground-level plume generated by a stationary jet engine were then completed with the use of two multi-detector teleradiometers and a contrasting panel that was located behind the plume (11). More sophisticated aerosol and radiative transfer models were developed to simulate visual air quality during the 1990s (12). Digital photos were then used to characterize visibility during the late 1990s (13).

Photographic techniques should quantify plume opacity over a wide range of ambient conditions and use digital cameras that are readily available at reasonable cost (~\$300 USD). The cost to implement a photographic method when compared to using Method 9 is less since training costs are reduced, and training can be completed in-house with a digital library of plume images without the need to generate actual plumes of known opacity at a "smoke school." Also, bias is reduced when compared with Method 9 since plume opacity values are derived from digital images using software with a pre-designed algorithm. Use of images to quantify plume opacity also provides photographic records of the plume and its surroundings at ambient conditions that are available for legal purposes.

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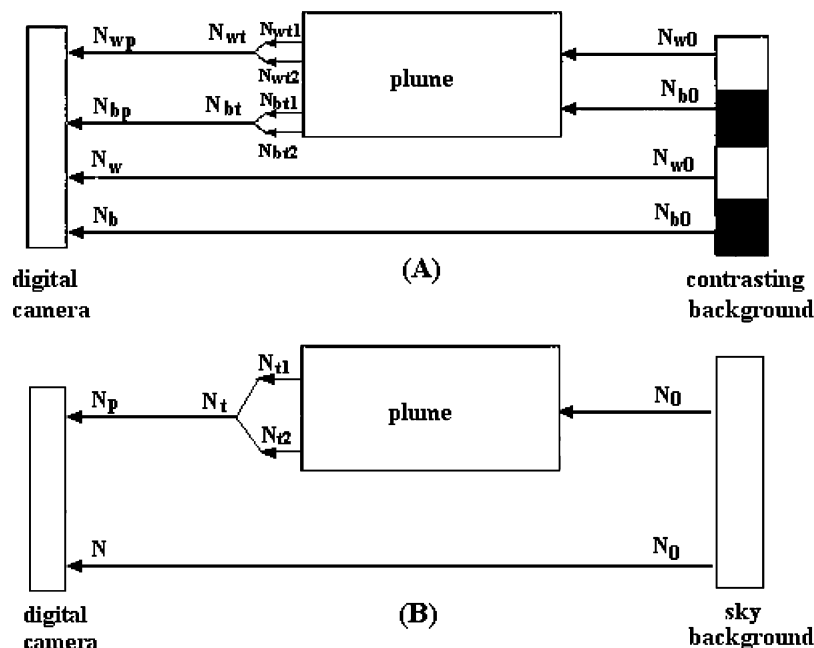


FIGURE 1. Schematic describing the contrast (A) and transmission (B) models to determine plume opacity.

The initial use of digital photography to quantify visible plume opacity was accomplished with the Digital Opacity Compliance System (DOCS) (14). DOCS uses a specific digital camera with software that is installed in the camera. The camera is self-calibrating for clear-sky backgrounds. To calculate the opacity of a plume, digital images are downloaded to a computer and the operator selects an area in the photograph which includes the part of the plume where opacity will be determined and the clear-sky background. The performance of DOCS was evaluated at USEPA-approved smoke schools for both clear-sky (15) and overcast-sky conditions (16).

## Methodology

During this study, the Digital Opacity Method (DOM) was developed to quantify plume opacity with a wide range of ambient daytime conditions, using readily available low-cost digital cameras, and a new digital image processing technique that is based on first principles. The cameras are calibrated to accurately characterize the camera's response curve. Calibration of a manual-exposure controlled digital camera consists of taking a series of photographs of a scene that has stable and uniform radiance (e.g., part of a blue sky or a white wall with diffusive reflection) (17). These photographs are obtained using a range of exposure times, with each increase in exposure time resulting in an increase in pixel values for that scene. The exposure for each photograph is a quantity proportional to the product of exposure time, aperture area, and incident radiance. The exposure for each photo and its corresponding mean pixel value are then used to obtain a camera response function from a polynomial regression relating  $\log(\text{normalized exposure}) = f(\log(\text{pixel value}))$ . Therefore, the radiance ratio between any two areas A and B in a photograph can be determined from corresponding pixel values,  $PV_A$  and  $PV_B$ , through the calibrated camera response function. The ratio of the exposure for areas A in a photograph to the exposure for area B in the same photograph is equal to the radiance ratio for those same areas because the exposure time and aperture size are the

same for both areas since they are in the same photo. Therefore,

$$\log \left( \frac{\text{radiance for area A}}{\text{radiance for area B}} \right) = \log \left( \frac{\text{exposure for area A}}{\text{exposure for area B}} \right) = f(\log(PV_A)) - f(\log(PV_B))$$

Automatic-exposure controlled cameras are calibrated with a similar procedure, while also using the manual-exposure controlled camera as part of the calibration (17). Hence, pixel values from two areas within a digital photograph are related to the ratio of radiance values for the scene that was photographed. Digital photographs of the plume are then analyzed by DOM with either the contrast or transmission models.

The contrast model quantifies plume opacity from a change in contrast between two contrasting backgrounds that are located behind the plume and next to the plume (Figure 1A). The difference in contrast between the backgrounds viewed with and without the plume is caused by the differences in radiances that are coming from these backgrounds. Contrast is determined by the ratio of the radiances coming from the bright area to that coming from the dark area of the contrasting background. The radiance ratio is then quantified from the corresponding pixel values by means of the camera's response curve. Therefore, pixel values from the photograph are directly related to plume opacity.

Pixel values used in the contrast model depend on  $N_{w0}$  and  $N_{b0}$ , which are radiance values that originate from the bright and dark parts of the background (Figure 1A), respectively.  $N_{wt1}$  and  $N_{bt1}$  are the attenuated radiance values that result from  $N_{w0}$  and  $N_{b0}$  after the light is scattered and/or absorbed by the plume, respectively.  $N_{wt2}$  and  $N_{bt2}$  are diffusive radiance values caused by sources of light other than the backgrounds (e.g., sunlight back-scattered from the plume and directed into the camera's line of sight toward the plume).  $N_{wt}$  is the radiance value resulting from  $N_{wt1}$  and  $N_{wt2}$ , and  $N_{bt}$  is the radiance value resulting from  $N_{bt1}$  and  $N_{bt2}$ . Finally,  $N_{wp}$  and  $N_{bp}$  are the equivalent radiance values recorded by the camera, in terms of pixel values. Similarly,  $N_w$  and  $N_b$  are the equivalent radiance values recorded by

the camera, in terms of pixel values caused by  $N_{w0}$  and  $N_{b0}$ , respectively, after passing through the plume-free atmosphere. Values for  $N_{wp}$ ,  $N_{bp}$ ,  $N_w$ , and  $N_b$  are then used to determine the plume's opacity by DOM as described by the following (17):

$$\text{Opacity} = 1 - \frac{N_{wp} - N_{bp}}{N_w - N_b} \quad (1)$$

The transmission model quantifies the opacity of a plume that has a uniform sky background (e.g., uniform clear or overcast sky) that is in contrast to the plume (Figure 1B). This model determines the plume's opacity based on the radiance from the plume and the radiance from the plume's background.  $N_0$  is the radiance from the uniform sky that is behind and next to the plume at the same height as the camera's line of sight.  $N$  is the equivalent radiance value recorded by the camera, in terms of pixel values, after  $N_0$  passes through the plume-free atmosphere:

$$N = N_0 T_r + N^* \quad (2)$$

where  $T_r$  is the transmittance of the plume-free atmosphere between the camera and the furthest boundary of the plume with respect to the camera.  $N^*$  is the path radiance along the same path, which can be estimated with an equilibrium radiance model for uniform illumination (clear sky or overcast sky) and negligible absorption (12):

$$N^* = N_0(1 - T_r) \quad (3)$$

Substitution of eq 3 into eq 2 results in  $N = N_0$ .

$N_{t1}$  is the attenuated radiance value that results from  $N_0$  after the light is scattered and/or absorbed by the plume, and  $N_{t2}$  is the diffusive radiance value caused by other sources of light than the uniform sky background (e.g., sunlight back-scattered from the plume and directed into the camera's line of sight toward the camera).  $N_t$  is the radiance value resulting from  $N_{t1}$  and  $N_{t2}$ . According to the definition of opacity,  $O$ ,

$$O = 1 - \frac{N_{t1}}{N_0} = 1 - \frac{N_t - N_{t2}}{N} \quad (4)$$

$N_p$  is the equivalent radiance value recorded by the camera, in terms of pixel values, caused by radiance from the plume and path radiance of the atmosphere,

$$N_p = N_t T_{ra} + N_a^* \quad (5)$$

where  $T_{ra}$  and  $N_a^*$  are the transmittance and path radiance of the atmosphere between the camera and the closer boundary of the plume with respect to the camera, respectively.  $N_t$  is equated to  $N_p$  in this study due to negligible extinction and path radiance of the atmosphere along that same path (i.e.,  $T_{ra} \approx 1$  and  $N_a^* \approx 0$ ) based upon typical conditions experienced during the field campaigns described below. Therefore, eq 4 becomes the following:

$$O = 1 - \frac{N_p - N_{t2}}{N} \quad (6)$$

The cameras did not directly measure  $N_{t2}$ , which depends on the background sky radiance and plume opacity. However,  $N_{t2}$  is proportional to the product of sky background radiance,  $N_0$ , and the opacity,  $O$ :  $N_{t2} = KN_0O = KNO$ . The proportionality coefficient,  $K$ , was quantified for typical weather conditions and optical properties of the plumes' aerosol particles (17). The  $K$  values of 0.16 and 1.4 were used by the transmission model for black and white plume, respectively. Hence,  $N_{t2}$  is expressed as a function of  $N$  and plume opacity

in the transmission model and is substituted into eq 6 to describe opacity as a function of the ratio of  $N_p$  to  $N$  and  $K$ . The radiance ratio is quantified from the corresponding pixel values for plume and sky background by means of a camera response curve, and then the plume opacity is determined by DOM as described by:

$$\text{Opacity} = \frac{1 - \frac{N_p}{N}}{1 - K} \quad (7)$$

Overall, DOM is able to quantify plume opacity during the daytime with the contrast and transmission models. The contrast model is applicable if there is a contrasting background behind and next to the plume. Examples of such backgrounds for the contrast model include a clear-sky background and a dark background (e.g., dark tree or roof of building) for dark or bright plumes, a cloudy sky background and a dark background for dark or bright plumes, or the use of artificial contrasting backgrounds (e.g., black and white boards) for dark or bright plumes. The transmission model is applicable for plumes viewed in front of a uniform contrasting background when compared to the plume, such as a clear sky for dark or bright plumes, a uniform white cloudy sky for dark plumes, or other backgrounds with sufficient contrast with the dark or bright plumes. However, the transmission model is not applicable if the background does not have sufficient contrast with the plume, making it difficult to distinguish the plume from its background (i.e., white plume with a white background).

## Evaluation of DOM

Field campaigns to evaluate the performance of DOM were completed with a smoke generator that was operated by Illinois EPA personnel at Springfield, IL. The smoke generator included a stack where opacity levels were measured with a reference transmissometer. The stack's diameter was 30 cm and its outlet was 4.5 m above the ground.

**July 2003 Field Campaign.** The July 24, 2003 field campaign evaluated the performance of DOM using (1) the contrast model with two artificial contrasting backgrounds, and (2) the transmission model with a clear-sky background (Figure 2A). Two masts were installed near the exhaust stack of the smoke generator to mount the artificial contrasting backgrounds behind and next to the plume as the plume was emitted to the atmosphere. The backgrounds were 90 cm by 90 cm square boards that were painted black and white. A manual-exposure controlled digital camera (Canon Powershot G3, located to the west) and an automatic-exposure controlled digital camera (Sony DSC-S30, located to the east) were used simultaneously to quantify the plumes' opacities. Each camera was positioned on a tripod and located 1.4–1.7 m above the ground to provide clear views of the plumes. The positions of the cameras and artificial backgrounds were arranged so that one artificial background was just behind the plume and the other artificial background was next to the plume for each camera. The cameras were located to the south of the stack and 16 m away from each other. Both cameras were 21.4 m away from the stack to allow for a minimum distance of at least three stack heights between the cameras and the base of the stack.

The tests started at 0% opacity and then increased to 100% opacity at 14 levels for the black plumes. White plumes were then generated with the same test sequence. Each camera took one photo every 15 s for a total of 24 photographs/camera at each opacity level and for both black and white plumes. The test began at 9 AM CST and ended at 3 PM CST, resulting in 1,405 photographs. The sun was oriented within the 208° sector to the back of the cameras for the entire duration of the campaign. Such sector's width was deter-



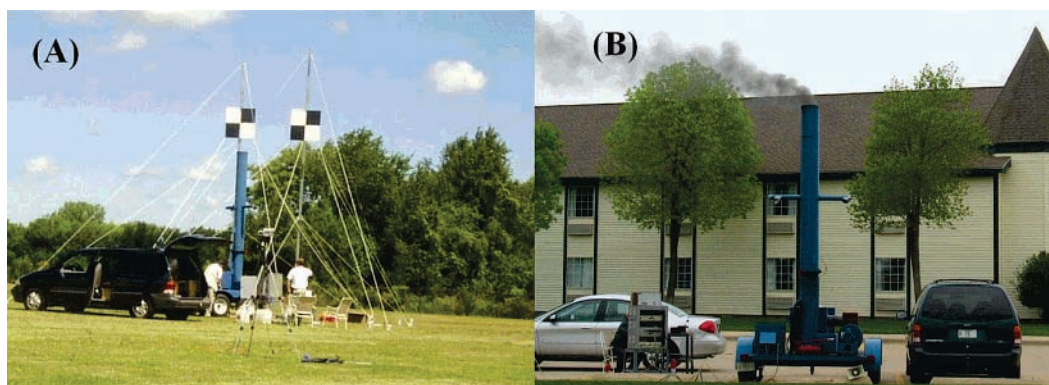


FIGURE 2. Photographs of field sites; smoke generator, camera on tripod, and backgrounds for July 2003 (A), and April 2004 (B) field campaigns.

TABLE 1. Hourly Weather Conditions During the Two Field Campaigns (18, 19)

time [hr:min]	ambient temperature [°C]	relative humidity [%]	pressure [hPa]	wind speed [km/hr]	sun position	
					altitude [°]	azimuth [°]
July 2003 Field Campaign						
8:54	20	78	1021	0.0	33	91
9:54	22	69	1021	5.6	45	102
10:54	23	57	1021	0.0	56	106
11:54	24	53	1021	7.4	65	137
12:54	26	54	1020	11.1	70	173
13:54	26	47	1020	9.3	67	211
14:54	26	47	1020	5.6	59	237
April 2004 Field Campaign						
8:54	10.6	71	1016	25.9	41	111
9:54	10.6	74	1015	24.1	52	127
10:54	11.1	69	1016	27.8	59	148

mined by the location of the camera to obtain the appropriate background to take the pictures and the location of the sun during the field campaign. There were cloud-free conditions during the morning with the formation of overcast clouds during the afternoon (Table 1).

**April 2004 Field Campaign.** The April 22, 2004 field campaign was completed with the same smoke generator that was used for the first field campaign (Figure 2B). This campaign occurred during an EPA-approved smoke school to evaluate the performance of DOM with overcast conditions and intermittent rain. The sun was oriented within an 88° sector to the back of the camera for the duration of the campaign.

This field site provided a roof as the dark background and a bright overcast sky as the contrasting background. The manual-exposure controlled camera (Canon Powershot G3) was located 30 m to the south of the smoke generator and 1.4–1.7 m above the ground. The camera was carefully oriented so that the roof ridge was at one stack diameter above the outlet of the stack, which allowed the contrasting backgrounds to be at the same height behind and next to the plume. Such orientation allowed for the use of DOM's contrast method to quantify plume opacity for dark and bright plumes and the transmission model for dark plumes. The white overcast sky precluded the use of the transmission model to determine plume opacity for the white plumes because there was insufficient contrast between the overcast sky background and the white plume. The dark-roof and the cloudy-sky backgrounds were used as the contrasting background for the contrast model during this campaign. The change in contrast between the roof and sky backgrounds when observed through the plume and next to the plume

was determined from each digital photograph when using the contrast model.

This smoke school consisted of two tests with each test consisting of 25 black plumes with random levels of opacity and then 25 white plumes with random levels of opacity. The smoke reading portion of the smoke school was limited to a total of two tests during 1 day instead of the typical six to eight tests during 2 days due to inclement weather that included cold temperatures, cloudy skies, high winds, and intermittent rain (Table 1). Opacity values ranged between 5% and 80% for each of the black and white plumes. The camera took two photographs for each plume and the opacity values from those photographs were averaged to provide an individual plume opacity. The tests occurred between 9 AM CST and 11 AM CST, resulting in 200 photographs.

Method 9 requires that an observer have an individual opacity error ( $d_i$ ) ≤ 15% and an average opacity error ( $\bar{d}$ ) ≤ 7.5% for all 50 black and white plumes during a particular test for the observer to be certified for 6 months. The individual opacity error ( $d_i$ ) is the absolute error between an individual opacity value measured by the in-stack transmissometer (i.e., "standard" =  $0_{2,i}$ ) and the observed opacity value provided by the human or digital camera (i.e., "observed" =  $0_{1,i}$ ) as described by the following:

$$d_i = |0_{1,i} - 0_{2,i}|$$

where subscript  $i$  represents each corresponding measurement and observation for all 50 plumes. The average absolute opacity error ( $\bar{d}$ ) is defined as

$$\bar{d} = \frac{\sum_{i=1}^n |d_i|}{n}$$

where  $n$  is the number of paired observations.

## Results and Discussion

**July 2003 Field Campaign.** All of the digital photographs were analyzed to determine plume opacities using the contrast model. However, only the photographs of the black plumes were analyzed using the transmission model because overcast conditions formed later that day making it difficult to distinguish between the white plumes and the cloudy background.

Individual opacity errors for results from DOM are compared to USEPA's acceptable levels of error for black plumes and white plumes in Figure 3. The solid line represents a perfect 1:1 correspondence between modeled opacity values obtained from DOM and the measured opacity values that

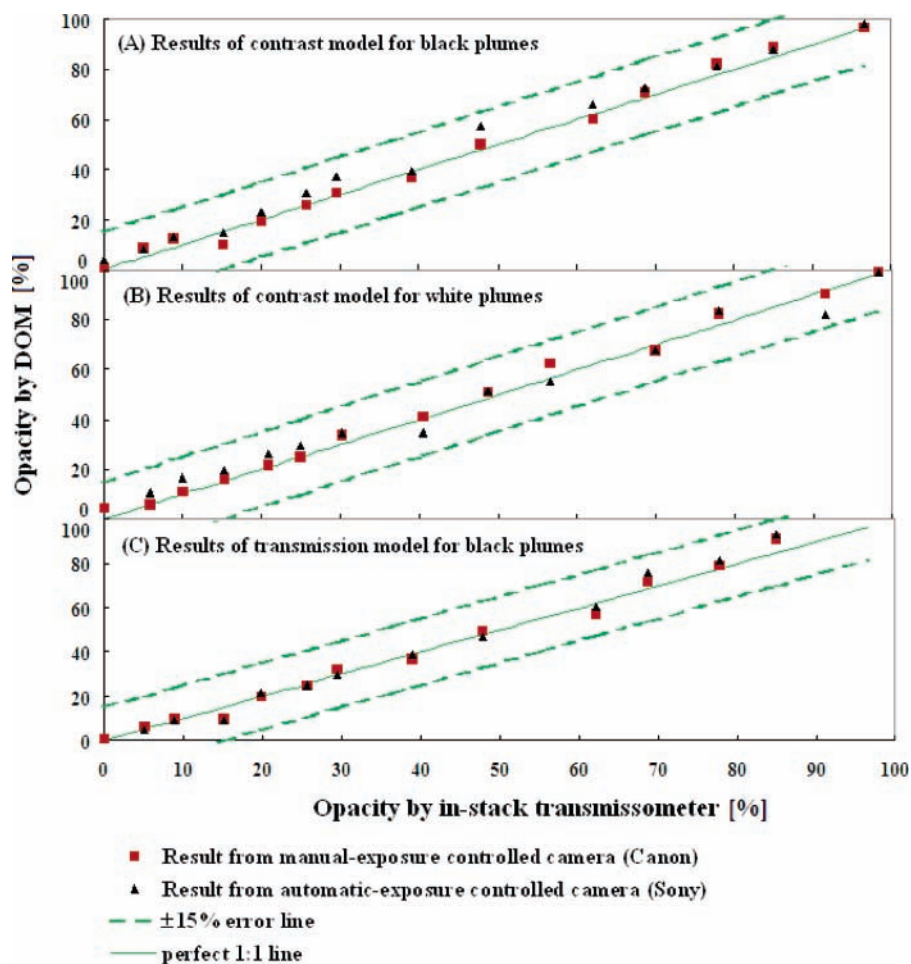


FIGURE 3. Comparison of individual opacity errors for DOM results to the USEPA-acceptable opacity error for the July 2003 field campaign

were obtained from the in-stack transmissometer. The bold dashed line is USEPA's acceptable 15% limit for the individual opacity errors.

Results from the contrast model compare well to the results from the in-stack transmissometer with all of the individual errors  $\leq 15\%$ , and 95% of these results  $\leq 7.5\%$ . Results from the transmission model for black plumes also compare well to the results from the transmissometer with all of the individual errors  $\leq 15\%$ , and 89% of these results  $\leq 7.5\%$ . Therefore, the errors associated with the opacity values obtained with the contrast model and the transmission model (excluding white plumes with a white cloudy background) satisfy the individual error limits specified in Method 9. The results from both models have good linearity with  $R^2$  values  $> 0.97$  for all linear regressions.

All of the average opacity errors for the contrast and transmission model results were  $< 7.5\%$ . Average opacity errors of 2.2% and 4.3% were obtained for the contrast model when using the manual-exposure and automatic-exposure controlled cameras, respectively. Average opacity errors of 3.2% and 3.3% were obtained for the transmission model when using the manual-exposure and automatic-exposure controlled cameras, respectively. Therefore, the error associated with the manual-exposure controlled camera is 36% lower than the error for the automatic-exposure controlled camera. The larger errors for the automatic-exposure controlled camera were most likely due to the calibration procedures, which depend on the calibration of the manual-exposure controlled camera. Average error results are categorized into seven opacity ranges between 0% and 100% and are compared to USEPA's acceptable average opacity error of 7.5% in Figure 4. All of the results indicate that DOM

quantifies plume opacity well within USEPA's acceptable error limits. The lower opacity errors obtained when using the manual-exposure controlled camera and the contrast model is apparent. The differences in opacity errors that are obtained by the two different cameras when using the transmission model are not as apparent as the differences in opacity errors when using the contrast model.

**April 2004 Field Campaign.** All of the photographs were analyzed for plume opacity using the contrast model with the already existing dark roof and bright overcast sky backgrounds. However, only the transmission model was used for the black plumes with the overcast cloudy-sky background.

Comparison of opacity results from DOM to opacity results from the in-stack transmissometer provides encouraging individual opacity errors that are all  $\leq$  USEPA's acceptable error of 15% (Figure 5). The solid line represents a perfect 1:1 correspondence between opacity values obtained from DOM and the transmissometer. The bold dashed line is USEPA's acceptable error limit of 15% for the individual opacity errors. These errors range from 0.2% to 13.8% for the contrast model and range from 0% to 14.8% for the transmission model. The results from both models and for both tests have good linearity with  $R^2$  values  $> 0.94$  for all linear regressions.

Average opacity errors obtained when comparing opacity results from DOM and the transmissometer are all  $< 7.5\%$ . Average opacity errors ranged from 3.6% to 5.4% and from 3.5% to 4.7% for results from the contrast and transmission models, respectively. Average error results are categorized into seven opacity ranges and are compared to USEPA's acceptable average opacity error of 7.5% in Figure 6. Once

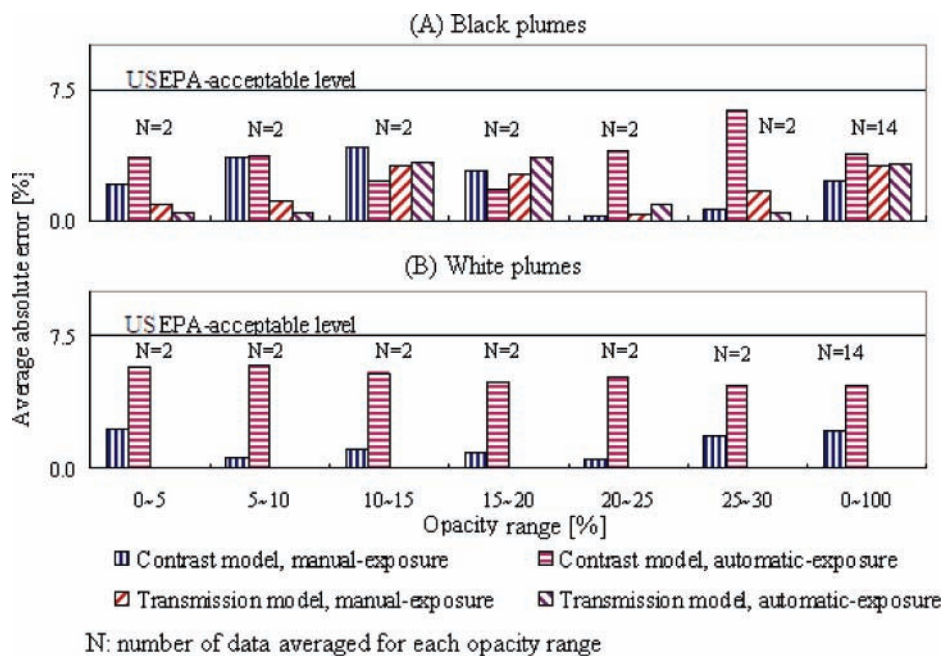


FIGURE 4. Comparison of average opacity errors for DOM results to the USEPA-acceptable level for July 2003 field campaign.

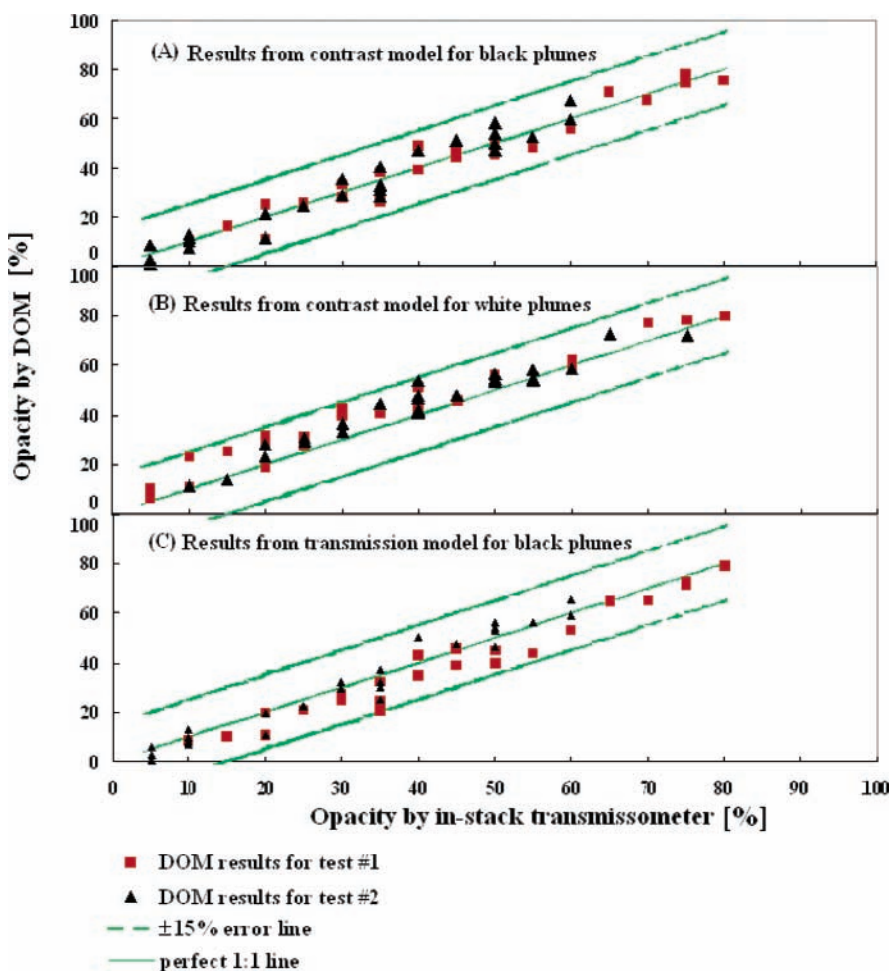
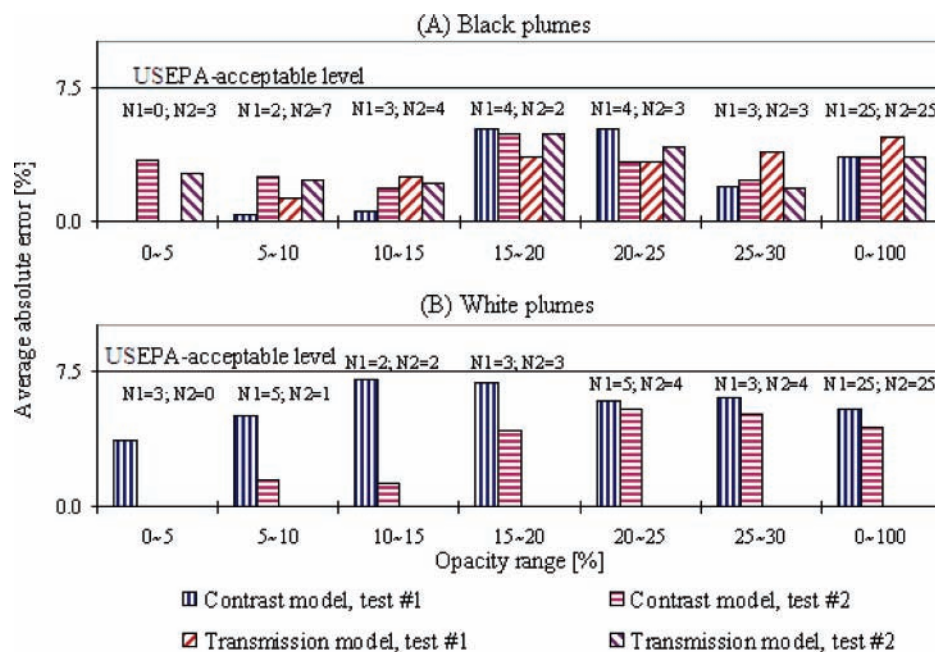


FIGURE 5. Comparison of individual opacity errors of DOM results to the USEPA-acceptable level for the April 2004 field campaign.

again, all of the results indicate that DOM quantifies plume opacity well within USEPA's acceptable error limits. The average opacity errors obtained with the manual-exposure controlled camera that are described in Figure 6 are larger than the corresponding values described in Figure 4. The

larger errors are likely the result of more challenging environmental conditions and the reduced contrast between the plumes and their respective backgrounds that existed during the 2004 campaign. The July 2003 field campaign was completed while using backgrounds with more contrast and





N1: number of data averaged for each opacity range in test #1  
N2: number of data averaged for each opacity range in test #2

FIGURE 6. Comparison of average opacity errors of DOM results to the USEPA-acceptable level for the April 2004 field campaign

during clearer sky, low wind, and no rainfall conditions, which are more favorable than the conditions that existed during the April 2004 field campaign.

**T-Test of Average Error Results.** As previously described, results from DOM's contrast and transmission models had individual errors  $\leq$  the USEPA-acceptable limit of 15% and average opacity errors  $\leq$  the USEPA-acceptable limit of 7.5%. However, it is useful to evaluate the average opacity errors for results from DOM to see if they are significantly  $\leq 7.5\%$  based on the Student *t*-test (20). *t*-tests were performed for all plume categories during the July 2003 and April 2004 field campaigns. All of the average opacity errors are significantly  $\leq 7.5\%$  at a confidence level of 99% (i.e., level of significance = 0.01).

**Discussion of Results from Both Field Campaigns.** The performance of DOM to quantify plume opacity was tested under both favorable weather conditions (i.e., sunny, relatively clear sky, and low wind) and unfavorable weather conditions (i.e., overcast sky, intermittent rain, and high wind). All of the results from the contrast and transmission models had opacity errors less than the maximum allowable values established by USEPA with the sun located in a 208°-sector behind the cameras. Figures 4 and 6 show that the average opacity errors of the April 2004 field campaign are 67% higher than those of the July 2003 field campaign for the contrast and transmission models. Also, the data points in Figure 5 are more scattered than those in Figure 3. The better performance of DOM during the July 2003 field campaign is attributed to the better weather conditions (e.g., sunny, relatively clear sky, and low winds vs overcast cloudy sky and strong winds (Figure 2, Table 1)), and high contrast backgrounds (black/white board vs roof/sky (Figure 2)). The data points in Figure 5C are more scattered than the data points in Figure 3C because the transmission model relies on the sky as the background and is therefore more sensitive to the sky's condition than for the contrast model. The sky was overcast during the 2004 field campaign. The homogeneity of the sky and the plume/sky contrast during the 2004 field campaign were not as ideal as those for the 2003 field campaign (Figure 3). However, DOM satisfied USEPA's

requirements in terms of the individual and average opacity error limits during the tested weather conditions. A maximum wind speed of 30 km/hr is recommended to successfully use DOM to determine plume opacity. This limitation is due to the conditions experienced in the field while successfully meeting error limits established by USEPA for Method 9. The performance of the transmission model is compromised when the contrast between the background and plume approaches zero due to difficulties in distinguishing the plume from the background. In such a situation, the photographer needs to choose an orientation to view the plume against a contrasting background and use the contrast model to quantify the plume's opacity. For example, the roof and sky were selected as the backgrounds of the plumes in the April 2004 field campaign, and the plumes' opacities were calculated based on the change in contrast when using the roof and sky as backgrounds. Although eq 1 can give exact plume opacity values with any contrasting background behind and next to the plume, error could result when using a low contrasting background (e.g., sky/roof background that existed during the 2004 field campaign) when compared to using a high contrasting background (e.g., black/white boards that existed during the 2003 field campaign). That is especially the case for white plumes. The positive bias in plume opacity values for white plumes as determined by the contrast method when compared to the transmissometer is apparent in Figure 5B. The bias occurs because the overcast sky was so bright that it was difficult for the camera to distinguish the white plumes from the bright white background. Therefore,  $N_{wp}$ , which should be  $> N_w$ , is approximately equal to  $N_w$ , which results in larger opacity values determined by the camera when compared to opacity values measured by the in-stack transmissometer. Despite the positive bias associated with the contrast model, results from the contrast model obtained during the April 2004 field campaign demonstrated that DOM works well by achieving individual and average opacity errors within USEPA acceptable limits. This gives DOM more flexibility for field applications, when clear sky conditions are not available.



As discussed previously, DOM's accuracy in quantifying plume opacity depends not only on the digital camera used, but also the factors such as background, weather conditions, and viewing geometry, which are also factors affecting the accuracy of Method 9. However, the results obtained from the two cameras used during the July 2003 field campaign agree well with each other (Figure 3). The average absolute difference between the results for the two cameras is 3.0%. The consistency between the results from the two cameras used during the July 2003 field campaign shows that these calibrated cameras performed consistently and met Method 9 error limit requirements. However, cloudy weather, low contrast background, and high wind adversely affected DOM's accuracy according to the results from the field campaigns.

DOM's advantages over Method 9 include its objectivity, low cost, permanent documentation, in-situ performance, and near real-time response. It is easy to implement and the software is available in a Windows based user-friendly software package. In addition, DOM can satisfy USEPA's Method 9 requirements under both clear and overcast conditions, and the contrast model can be used when a sky background is not available. Future work is needed to expand DOM's abilities to quantify the opacity of plumes from fugitive emissions and during nighttime conditions. Further testing and improvements of DOM should lead to even greater gains in performance for digital-photography-based opacity measurement systems.

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